

# Evaluation of the recorded ground motions for the unusual earthquake of 13 August 2006 ( $M_w$ 5.3) in Michoacán México

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**Abstract** The focal mechanism of the moderate earthquake of 13 August 2006  $M_w=5.3$ , which occurred in the border coastal area between Michoacán and Colima, México, is unusual. As shown by the Global Centroid Moment Tensor (CMT) project and the Servicio Sismológico Nacional de Mexico (SSN), the thrust mechanism is striking almost perpendicularly to the majority of earthquakes occurring along the subduction zone of the Mexican Pacific continental margin which commonly strike nearly parallel to the trench. The

purpose of this study is to analyze the observed ground motions of this particular event relative to those of the common events. First, we apply the H/V technique to verify that the stations involved in this study are nearly free of site effects. Then, we compare the observed ground motions with (i) three empirical ground motion prediction equations (GMPEs) appropriate for the region, (ii) ground motions of four real earthquakes with the common mechanism, and (iii) the Fourier spectrum of a selected common event.

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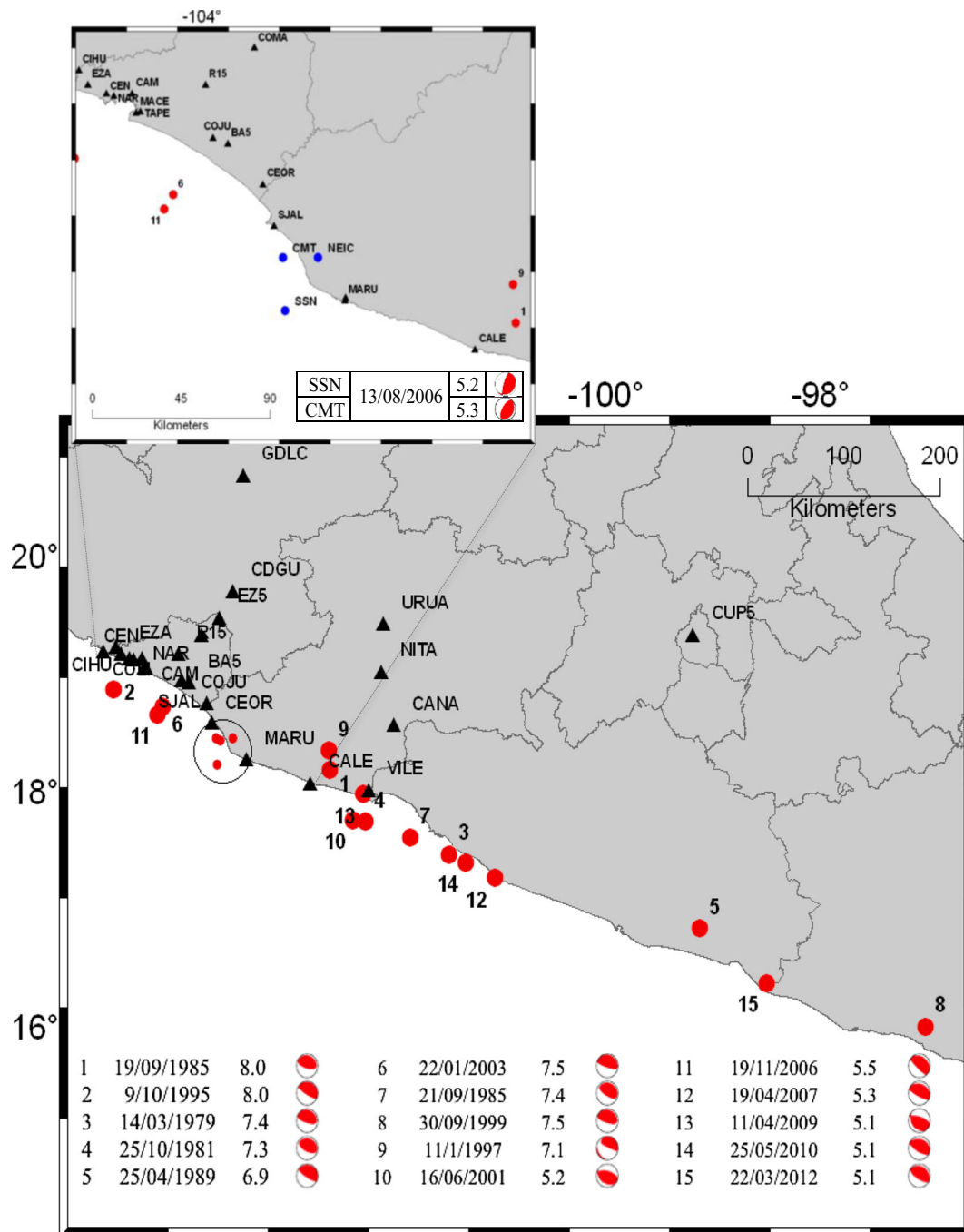
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## 1 Introduction

On the 13 August 2006, an unusual earthquake of magnitude  $M_w=5.3$  occurred at 15:14:28.4 GMT. The epicenter of this event was located by the official seismological agency of México, Servicio Sismológico Nacional (SSN), in the coastal area between the states of Michoacán and Colima, México (Fig. 1). For this event, the Global Centroid Moment Tensor (CMT) project database reported the following parameters (Fig. 1 and Table 1): a location (latitude, longitude, depth)=(18.45° N, 103.63° W, 23.5 km), a centroid moment tensor solution with a seismic moment of  $M_o=6.89e+20$  Nm, equivalent to an  $M_w=5.3$  event, and with focal mechanism (strike, dip, and rake)=(211°, 67°, and 87°).



**Fig. 1** Geographic location of events used in this study. *Red filled circles* represent some significant moderate and severe events with strike nearly parallel to the Middle America Trench. Their focal mechanisms are illustrated in the table inset. The *blue filled circles*

of inset figure show the epicentral location of the 13 August 2006 earthquake estimated by SSN, Global CMT project, and NEIC. *Black triangles* show the regional acceleration stations, used in the present study

The importance of the 13 August 2006 event is that it is the first event recorded in this region that has a focal mechanism that is uncommon for this area (Fig. 1).

Namely, the nodal planes of the focal mechanism for this event strike perpendicular to the trench axis, nearly perpendicular to the nodal planes of the vast majority of

**Table 1** Location and focal mechanism reported by the Global CMT project and that calculated by using regional broadband stations of SSN

	Centroid location Latitude N (°), longitude E (°), depth (km)	Focal mechanism Strike (°), dip (°), rake (°)	$M_w$
SSN	18.23, -103.62, 13.00	197, 76, 77 62, 19, 133	5.2
Global CMT Project	18.45, -103.63, 23.5	211, 67, 87 38, 23, 96	5.3

the earthquakes occurring along the subduction zone of the Mexican Pacific margin (i.e., the northern part of the Middle America Trench). The occurrence of seismic events with these characteristics is justified in regions with complex tectonics. However, this is a very scarce seismic phenomenon, as has been observed in many regions of the world. For example, Astiz et al. (1988) conducted a study of the larger, tectonically significant events around the world and the relation of intermediate-depth earthquakes to shallower seismicity. From their final catalog that includes 335 events, they found that only 10 % correspond to normal or reverse-fault events with a strike significantly oblique to the trench axis (similar to the event addressed in this study). Additionally, from these 10 %, none of the events listed in the database of Astiz et al. (1988) are located in the Mexican subduction zone. Currently, the SSN is not officially reporting the focal mechanism of these events, so the most complete catalog of this type of information is the Global CMT project. Our review of this catalog from 1974 to the present shows no other event with these characteristics in this region. Indeed, our seismic catalogs derived from the events recorded in our temporal and permanent seismic networks in the region show no other event with this characteristic. For the above reasons, we consider that the moderate 13 August 2006 earthquake,  $M_w$  5.3 (henceforth referred to as the unusual event), is uncommon in the subduction zone of Mexico.

The objective of this study is to investigate the level of the ground motions generated by this particular and unusual event in comparison with those generated by a common event (strike nearly parallel to subduction). To this end, we compared peak ground acceleration (PGA) of the unusual event with three existing ground motion prediction equations (GMPEs) adequate for the region.

The GMPEs that consider earthquake data from the Mexican subduction tectonic environments and used in

this study to compare with the unusual event are: (1) the empirical GMPE of Ordaz et al. (1989) who used subduction earthquakes from the Mexican Pacific coast, (2) the empirical GMPE of Youngs et al. (1997) which considers subduction earthquakes from around the world, and (3) the empirical GMPE of Arroyo et al. (2010) which considers Mexican interplate earthquakes. We compare the three GMPEs with the following two parameters of the unusual event: the PGA and the 5 % damped pseudo-acceleration response at three structural periods between 0.1 and 3 s (0.3–10 Hz).

Besides the comparisons with GMPEs, we compare ground motions of the unusual event with real data from earthquakes with magnitudes ranging between 5.1 and 5.5 and with a strike nearly parallel to the trench axis. It is necessary to mention that before proceeding with the comparisons, and in order to discard the site effect, we carry out a study to obtain the spectral ratios H/V in the sites used in the comparison.

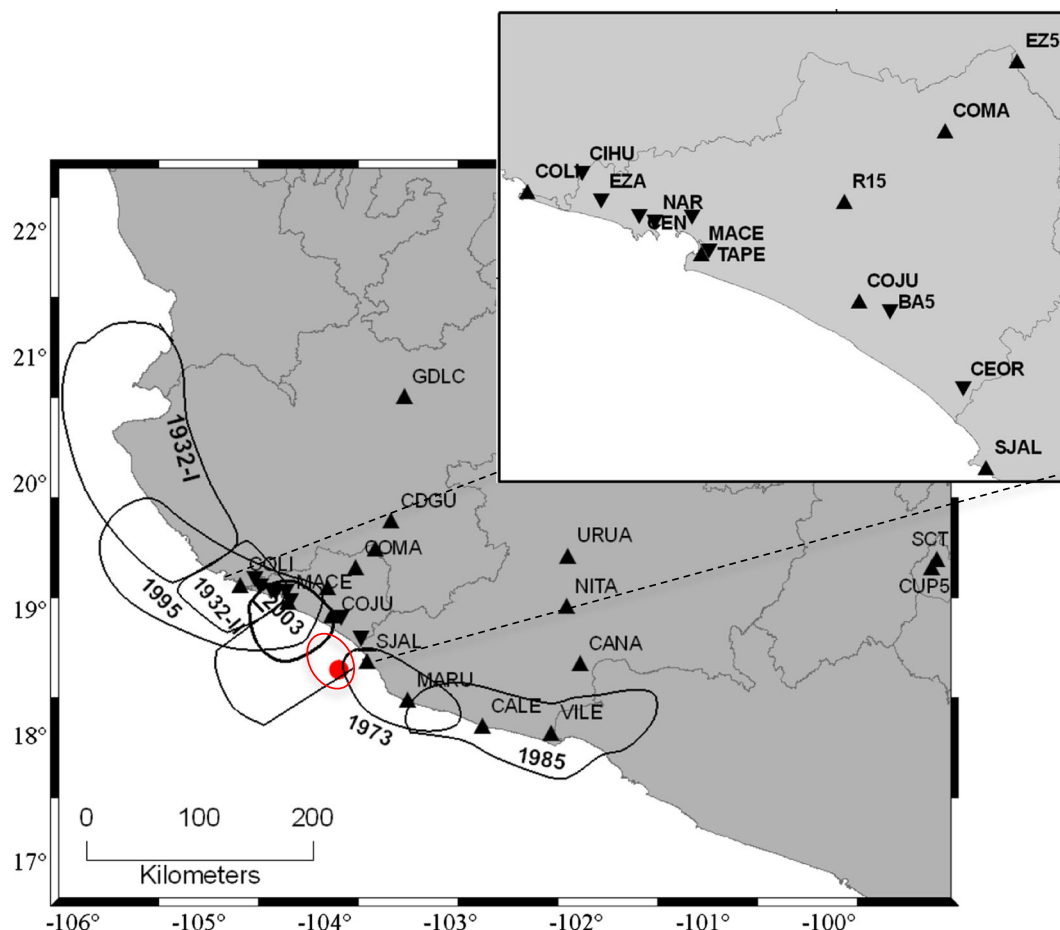
## 2 Historic seismicity and tectonic environment of region and its relation with unusual event

Although several severe earthquakes have been located and studied in this region of subduction (e.g., Santoyo et al. 2006; Reyes et al. 1979; Singh et al. 1985; Astiz et al. 1987; Nishenko and Singh 1987; Singh et al. 2003; Mendoza and Hartzell 1999; Yagi et al. 2004; Ramirez Gaytan et al. 2010, 2011; Quintanar et al. 2011), the 13 August 2006 earthquake is interesting to study because the historic seismicity of region where the unusual event was recorded shows that the seismic hazard must be considered to be high. This is one reason why it is necessary to put attention on the unusual event. This event occurred near the border of a small seismic gap (as defined by Astiz et al. 1987; Nishenko and Singh 1987; Quintanar et al. 2011) situated between the rupture area

of the 2003 Tecoman earthquake and the rupture area of the 30 January 1973 earthquake ( $M_w$  7.3) defined by Santoyo et al. (2006); Reyes et al. (1979). Specifically, Quintanar et al. (2011) show that the aftershock area of the Tecoman earthquake (Fig. 2) lies north of the southern boundary of the southern Colima Graben and that the aftershock area encompassed part of the rupture area of the 1932 and 1995 earthquakes. The region between the limits of the rupture areas of the 1995 and the 1973 earthquakes has been called the Colima seismic gap. The northwest half of this gap ruptured with the Tecoman earthquake in 2003. The other half of the gap, roughly to the southeast, remains quiet (Quintanar et al. 2011). For the adjacent region defined by the 30 January 1973 earthquake ( $M_w$  7.3), Reyes et al. (1979) estimate an average slip of 144 cm. For this region, plate

motion models predict a convergence rate between the Cocos and North American plates of between 5.0 and 6.0 cm/year (e.g., DeMets et al. 2010). The above results proposed by DeMets et al. (2010) suggests a repeat time of about 25 to 30 years, which, considering the various uncertainties are in very good agreement with the interval of 32 years between the 1973 and the preceding 1941 earthquakes proposed by Reyes et al. (1979). However, based on the results of the studies of Quintanar et al. (2011) and Reyes et al. (1979) and because it has been 38 years since the last major earthquake (the 1973 event) occurred in this area, the seismic hazard of this region where our unusual event recorded must be considered to be high.

According to Astiz et al. (1988, 1989, Astiz and Kanamori 1986) and Lay et al. (1989), events similar

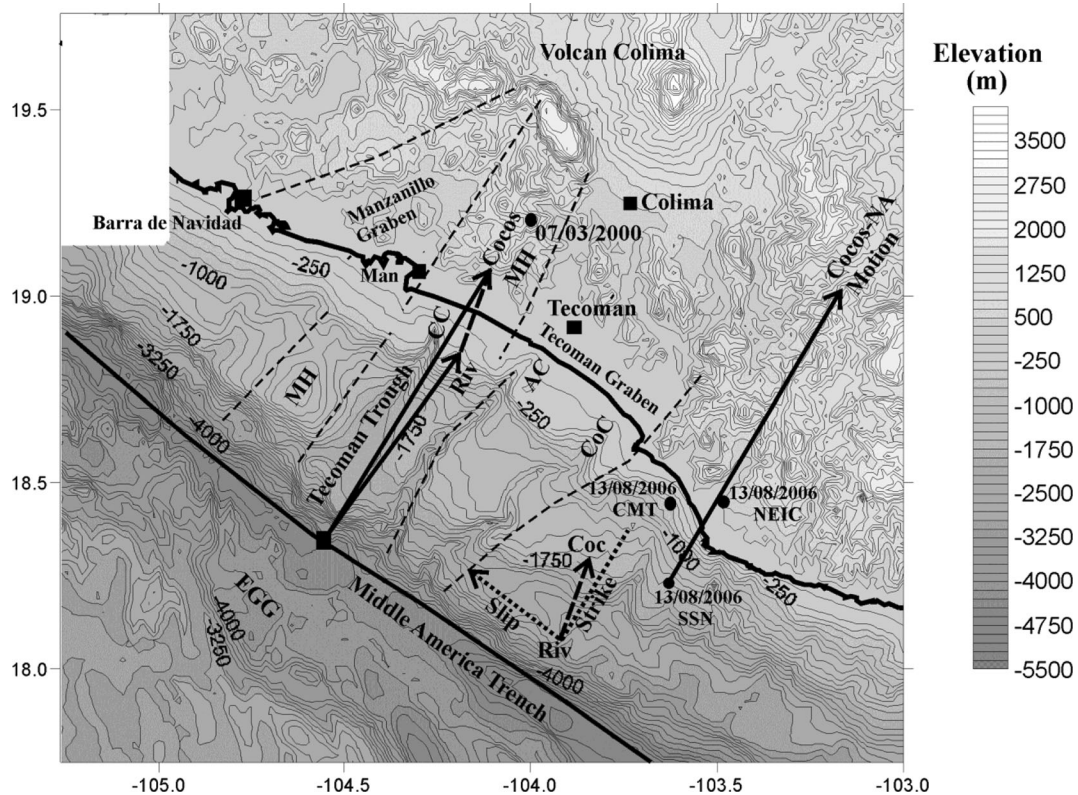


**Fig. 2** Location of the unusual event (solid red circle) analyzed in this study in the context of severe seismicity in the region. Red oval shows the seismic gap estimated by Quintanar et al. (2011). Areas enclosed by black curves show the rupture areas of historic, severe, earthquakes in the region (modified from Singh et al.

2003). Black triangles and inverted black triangles show the acceleration stations from different networks that operated in the region which provided strong ground motion data used in the present study

to that addressed in this study occur where the trench axis bends sharply, causing horizontal (parallel to the trench strike) extensional or compressional intraplate stress. The tectonic environment where the unusual event occurred is a tectonically complex area of the Mexican subduction zone near to a major plate triple junction formed by the Rivera, Cocos, and North American plates, the triple junction being located along the Middle America Trench (MAT) offshore of Manzanillo, México. The tectonic regime (Fig. 3) may be even more complicated as the interactions between these plates appears to have fragmented (1) the overriding North American plate into two kinematically independent crustal blocks, the Jalisco and Michoacán blocks, separated by the Colima Rift (e.g., Luhr et al.

1985; Johnson and Harrison 1990; DeMets and Stein 1990) and (2) the Cocos plate, forming a kinematically distinct plate, the northern Cocos plate, situated between the Orozco and Rivera transforms (Bandy 1992; Stock and Lee 1994; Bandy et al. 2000; Dougherty et al. 2012). The hypocentral depth estimated by the US Geological Survey’s National Earthquake Information Center (NEIC) (21.4 km), Global CMT project (23.5 km) and that of this study ( $13 \pm 7.3$  km) are all roughly consistent with an event occurring on the main plate interface (20 km) according to Pardo and Suárez (1995); however, the focal mechanism is clearly not that of an event occurring along the plate interface with slip in the direction of plate convergence.



**Fig. 3** Topographic/bathymetric contour map illustrating the main morphologic elements of the southern Colima rift. Also shown are the locations (solid circles) of the 13 August 2006 earthquake as reported by the Global CMT project, NEIC, and SSN as well as the epicenter of the 7 March 2000, normal event. The triangle at the intersection of the EGG and MAT is the velocity vector diagram illustrating the relative motions between the Rivera, Cocos, and North American plates at this plate triple junction. The Cocos-NA motion is also plotted at the SSN reported epicenter of the 13

August 2006 event. The Rivera-Cocos relative motion vector (dashed arrow) is also illustrated in the epicentral area of the 13 August event along with the slip direction (dotted arrow) and the strike of the fault plane (dotted line) of this event. Note that the strike of the fault plane is parallel to a major submarine canyon in the offshore area near the epicenters. EGG El Gordo Graben, MH Manzanillo Horst, Coc Cocos Plate, Riv Rivera Plate, Man Manzanillo, AC Armeria Canyon, CC Cuyutlan Canyon, CoC Coahuayana Canyon. (Modified from Bandy et al. (2005))

### 3 Data

To evaluate ground motions of moderate events, we use 23 observed records of the 13 August 2006 earthquake provided from three different data sources (Fig. 2). Table 2 shows the 24 stations of permanent and temporal networks that recorded the event; however, because one of these stations is located within soft soil, we remove this station from the analysis. Two of the sources are permanent seismic networks which consist of 14 Etna Episensor wideband accelerographs (from

d.c. to 200 Hz, recording at 200 samples per second) which are part of the Instituto de Ingeniería, Universidad Autónoma de México (IINGEN), and two Guralp CMG40T-DM24 flat response wideband velocity type seismographs (from 0.025 to 100 Hz, recording at 100 samples per second) which are part of the network Red Sísmica del Estado de Colima (RESCO). The third source of data was the temporal networks installed in the region as part of this project; the instruments used were (i) four Altus Etna wideband accelerographs (from d.c. to 100 Hz, recording at 100 samples per second) and

**Table 2** Soil type, peak ground acceleration, and quadratic mean acceleration for six different periods at each of the 24 stations considered in the present study

No	Station	$R$ (km)	Soil type	PGA (cm/s <sup>2</sup> )	Quadratic mean acceleration observed (cm/s <sup>2</sup> )					
					T 0.1 s	T 0.3 s	T 0.5 s	T 1 s	T 2 s	T 3 s
1	SJAL <sup>a</sup>	42.22	Rock	145.4	341.5	97.2	23.6	9.3	2.3	1.4
2	CEOR <sup>b</sup>	62.06	Rock	34.7	82.7	52.7	19.9	15.8	7.9	2.1
3	BA5 <sup>b</sup>	85.91	Rock	60.6	86.0	117.8	29.8	13.3	3.9	1.3
4	COJU	91.67	Rock	36.7	128.1	18.9	10.7	2.4	0.7	0.4
5	MARU <sup>a</sup>	19.81	Rock	58.7	180.0	47.4	34.0	6.4	1.7	0.8
7	TAPE <sup>b</sup>	121.68	Rock	14.5	30.8	8.2	3.1	0.9	0.3	0.1
6	R15 <sup>c</sup>	115.05	Rock	10.3	19.3	20.8	8.2	4.7	0.7	0.3
8	MANZ <sup>a</sup>	122.43	Rock	19.1	74.8	12.8	4.4	1.0	0.2	0.2
9	CAM <sup>b</sup>	130.55	Rock	15.2	49.1	19.8	4.1	1.1	0.3	0.2
10	NAR <sup>b</sup>	135.41	Rock	16.4	35.0	72.8	12.0	1.6	0.5	0.2
11	CEN <sup>b</sup>	138.75	Rock	5.8	15.5	12.9	2.6	1.3	0.3	0.1
12	COMA <sup>a</sup>	124.3	Rock	6.7	19.0	13.8	9.5	4.0	1.5	0.8
13	EZA <sup>b</sup>	147.63	Rock	12.3	26.1	23.8	5.6	1.0	0.3	0.2
14	CIHU <sup>b</sup>	155.56	Rock	9.7	20.2	26.5	6.9	1.5	0.3	0.1
15	EZ5 <sup>c</sup>	139.23	Rock	15.8	37.6	35.6	19.2	6.6	2.3	0.8
16	COLL <sup>a</sup>	161.83	Rock	5.0	13.5	6.6	2.3	0.7	0.2	0.1
17	CALE <sup>a</sup>	83.7	Rock	21.4	46.6	55.5	22.4	5.2	1.0	0.3
18	CDGU <sup>a</sup>	163.59	Rock	12.1	25.2	12.5	4.8	1.4	0.5	0.3
19	VILE <sup>a</sup>	142.06	Rock	3.2	4.2	13.1	7.3	1.6	0.4	0.1
20	NITA <sup>a</sup>	175.92	Rock	7.9	18.6	15.9	9.0	3.0	0.5	0.2
21	CANA <sup>a</sup>	168.15	Rock	6.0	16.1	10.4	5.0	1.7	0.3	0.1
22	URUA <sup>a</sup>	202.72	Rock	3.0	4.0	10.5	3.5	1.2	0.4	0.2
23	GDLC <sup>a</sup>	273.48	Soil							
24	CUP <sup>a</sup>	474.03	Rock	0.3	0.3	0.8	0.7	0.5	0.4	0.2

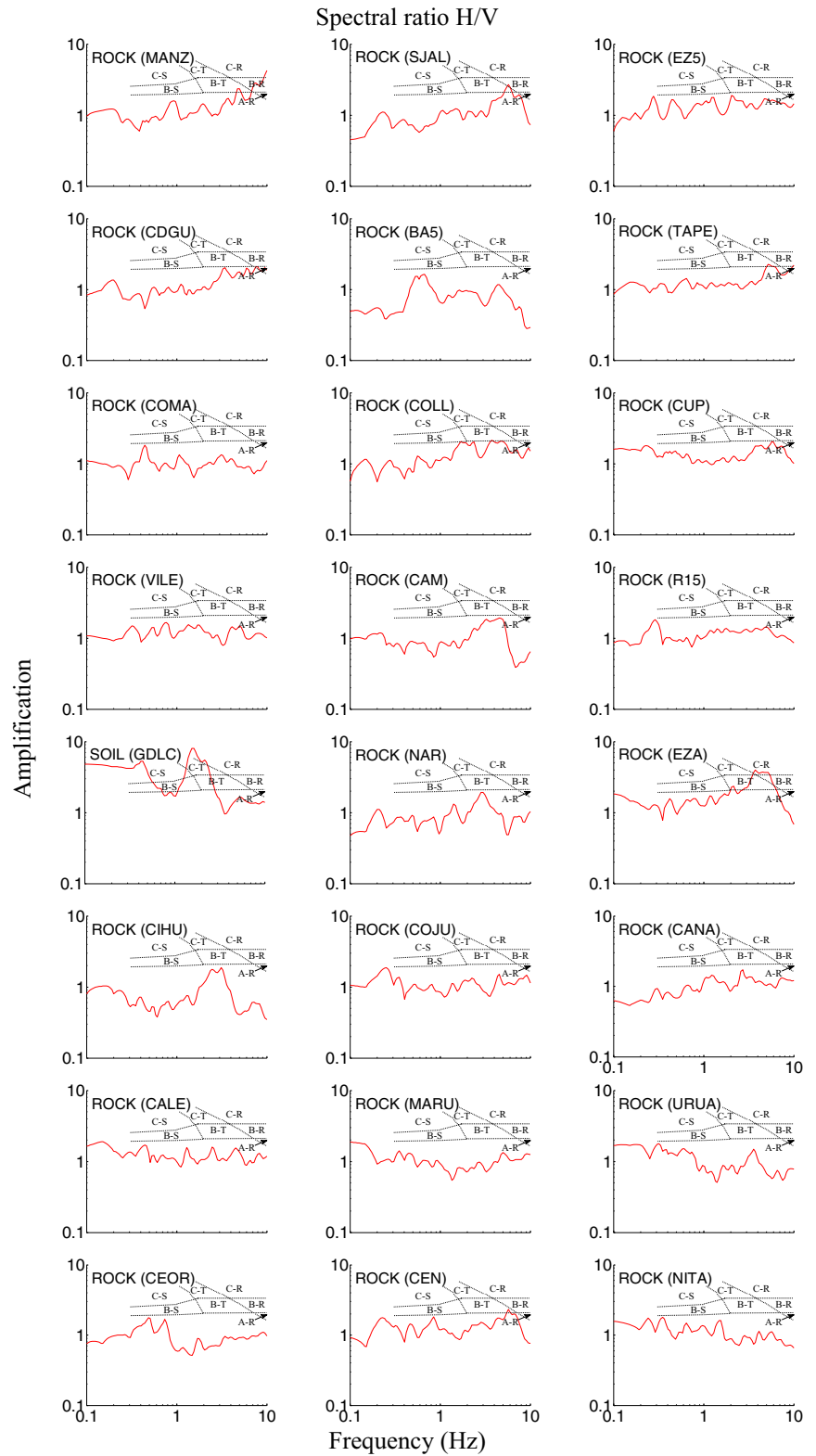
Only the 23 stations with a rock soil type were actually included in the analysis

<sup>a</sup>Stations from IINGEN

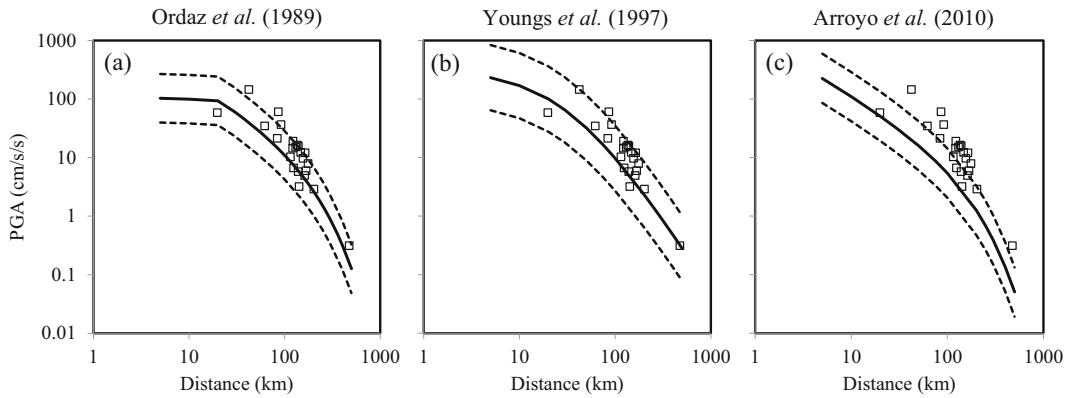
<sup>b</sup>Stations from temporary network parallel to trench

<sup>c</sup>Stations for RESCO

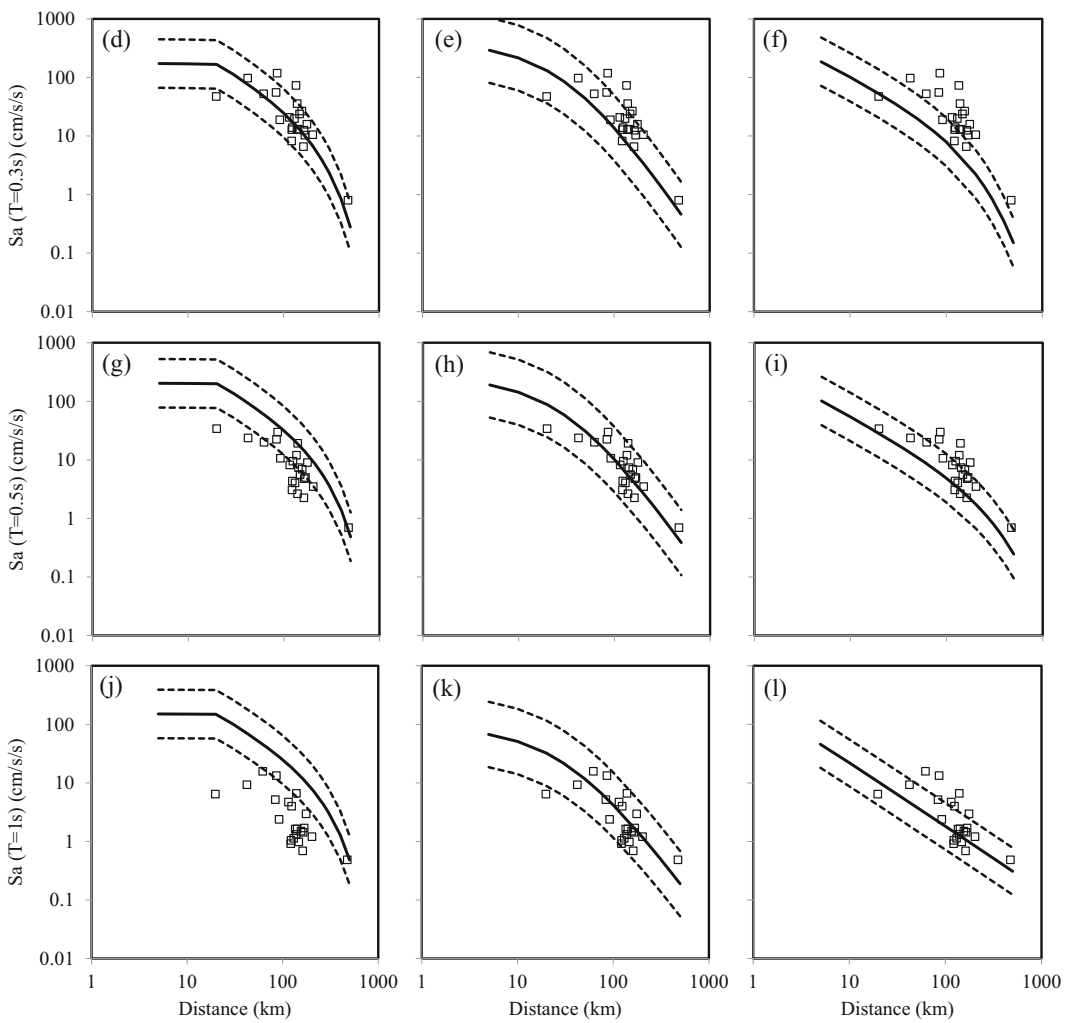
**Fig. 4** Spectral H/V ratios of acceleration for the 24 sites where the unusual event was recorded (red continuous line). Black dotted lines represent the zones of subsoil classification according to international German earthquake code DIN 4149:2005. Buildings in German earthquake regions—design loads et al. (2005). (R) Rock; (T) transition zone between rock and sediment; and (S) sediment basins with three soil conditions: (A) firm to medium-firm soil; (B) loose soil (gravel to coarse sands, marls); and (C) fine-grained soil (fine sands, loesses). Text in the upper left is the soil classification, while text in brackets is the name of the station



### COMPARISON OF OBSERVED PGA WITH PREVIOUS GMPE



### COMPARISON OF OBSERVED SPECTRAL ORDINATES AND PREVIOUS GMPE





◀ **Fig. 5** Comparison of three different GMPEs versus PGA (*top*) and response spectral ordinates at the structural periods of  $T=0.3$  s (*middle-top*),  $T=0.5$  s (*middle-bottom*),  $T=1$  s (*bottom*) for the moderate 13 August 2006  $M_w$  5.3, earthquake. Observed PGA and 5 % damping response spectral ordinates (*squares*, Table 2). *Solid lines* correspond to the horizontal component of the response spectra of earthquake predicted by the empirical GMPEs, and the *area between the black dashed lines* marks the 90 % confidence region corresponding to each GMPE used

(ii) four Geosig strong-motion recorders, with analog-digital converter, wideband accelerometers (from d.c. to 100 Hz, recording at 100 samples per second).

#### 4 Evaluation of the unusual event

To evaluate the unusual event, we conduct three different comparisons: The first is to compare the observed ground motions of the unusual event with three GMPEs adequate for the region, the second is to compare observed ground motions with real data of single events which strike nearly parallel to the trench, and the third is to compare the Fourier spectrum of the unusual event with a selected event with strike parallel to the subduction zone. As a preliminary task, and in order to conduct an adequate assessment between ground motions of the unusual event and the GMPEs, we conduct a study to verify that the stations involved in this study are free of site effects.

##### 4.1 Preliminary task, spectral ratio H/V site characterization

To conduct an adequate assessment between ground motions of the unusual event and the GMPEs, we verify that the stations involved in this study are basically free of site effects. From the 24 sites that recorded the unusual event, 14 records were provided by the IINGEN, and 2 records were provided by RESCO. The stations of these networks are presently being used in the study of near-source ground motions, seismic hazard assessment, earthquake scenarios, and seismic disaster prediction and have been used to derive two of the three GMPEs used in this study (e.g., Ordaz et al. 1989; Arroyo et al. 2010). The headers of the files generated by the stations of these networks classify these sites as hard soil. To verify this, after searching references that justify that classification, we determined by personal communication with the staff of IINGEN and RESCO that both institutions classified these sites as rock based on

information provided in geologic cartography and field inspection. As commented previously, the third source of data (remaining eight records) were provided by a temporary network parallel to subduction that we installed and operated in region in 2006. In this case, we select sites (small localities) where geologic cartography shows evident rocky outcrops. Once within localities, we looked for and moved to sites nearest to hills or rock.

As an additional check, we use the acceleration strong ground motions of the unusual event to plot H/V ratios of sites involved in this study. From Fig. 4, we observe that 23 of the 24 sites present amplifications lower than four times, and in the majority of the 23 sites, the amplification is below two times. In general, for these 23 sites, the spectral ratio H/V shows a flat response; such behavior corresponds to a hard soil. The obtained curves were compared according to international German earthquake code DIN 4149:2005. Buildings in German earthquake regions—design loads et al. (2005) in order to determine the classification. This code classifies the subsoil in three classes: rock (R); transition zone between rock and sediment (T); and sediment basins (S) with three soil conditions: firm to medium-firm soil (A); loose soil (gravel to coarse sands, marls) (B); and fine-grained soil (fine sands, loesses) (C). Figure 4 shows for each station presented in this study the spectral H/V ratios of unusual event overlain with the classification scheme based on DIN 4149:2005 site classes. According to this figure, only one station (GDLC) can be classified as C-S and amplifications are higher than nine times, consequently, we consider this site as a soil and this station was removed from the analysis.

##### 4.2 Comparison with empirical GMPEs

We extracted the PGA values of the horizontal component and computed this in agreement with the procedure followed in each empirical GMPE compared herein. Then, the geometric means of the two horizontal components at each station were also computed. Next, the intra-event standard deviation of each empirical GMPE for the unusual event is compared. In Fig. 5, we compare the PGA and 5 % damping response spectral ordinates for 23 stations located on hard soil and three structural periods ( $T=0.3$ , 0.5 and 1 s) of the moderate earthquake (squares) with the three predicted empirical GMPEs: Ordaz et al. (1989), Youngs et al. (1997), and Arroyo et al. (2010). The region between the dotted lines represents the prediction interval corresponding to a 90 %

**Table 3** Intra-event standard deviations (in natural logarithm units) of the predicted empirical GMPEs for earthquake with  $M_w=5.3$ 

Reference	PGA	$T=0.3$ s	$T=0.5$ s	$T=1$ s	$T=2$ s	$T=3$ s
Ordaz et al. (1989) <sup>a</sup>	0.58	0.58	0.58	0.58	–	–
Youngs et al. (1997) <sup>b</sup>	0.78	0.78	0.78	0.78	0.88	0.88
Arroyo et al. (2010)	0.59	0.58	0.58	0.56	0.47	0.44

<sup>a</sup> The total variability of the GMPE was assumed to be similar to the intra-event variability because it is not presented by Ordaz et al. (1989)

<sup>b</sup> The total intra-event of the GMPE was assumed to be the total variability minus the earthquake-to-earthquake variability

confidence level for each empirical GMPE used (Table 3). We consider that an observation falling outside the 90 % confidence interval can be considered as unusual in a statistical sense.

The results of the comparison with empirical GMPEs are presented in the present subsection. It is necessary to keep in mind that this comparison in principle is not intended to analyze the usefulness of GMPEs. The comparison is made with the goal to evaluate the level of ground motions of the unusual event in comparison with those generated by a common event of similar magnitude ( $M_w$  5.3). The next comparison takes into account the 90 % confidence interval (region between the dotted lines).

The results of comparison of empirical GMPEs with observed PGA of the unusual event is shown in Fig. 5a, b, c. First row of Table 4 (PGA) summarizes the results of this comparison in percentages. Columns 3 and 6 show that for the empirical GMPEs of Ordaz et al. (1989) and Youngs et al. (1997), observed PGA fits reasonably well with the respective empirical GMPE. However, this is not the case for the empirical GMPE of Arroyo et al. (2010); in this case, column 8 shows that observed PGA locate mostly above the 90 % confidence interval.

The results of the comparison of empirical GMPEs with three spectral ordinates are shown

in Fig. 5d to l. Rows 2, 3, and 4 of Table 4 (spectral ordinates at 0.1, 0.5, and 1 s, respectively) summarizes the results of this comparison in percentages. Figure 5g, j and column 4 of Table 4 show the only two spectral ordinates that locate below the confidence interval (60.9 and 87 %) and correspond to the spectral ordinates of the empirical GMPE of Ordaz et al. (1989). This behavior is not repeated, for the remainder cases of comparison (Fig. 5d, e, f, h, i, k, l and columns 2 to 10 of Table 4), where spectral ordinates fit or lie above the 90 % confidence interval of the empirical GMPEs.

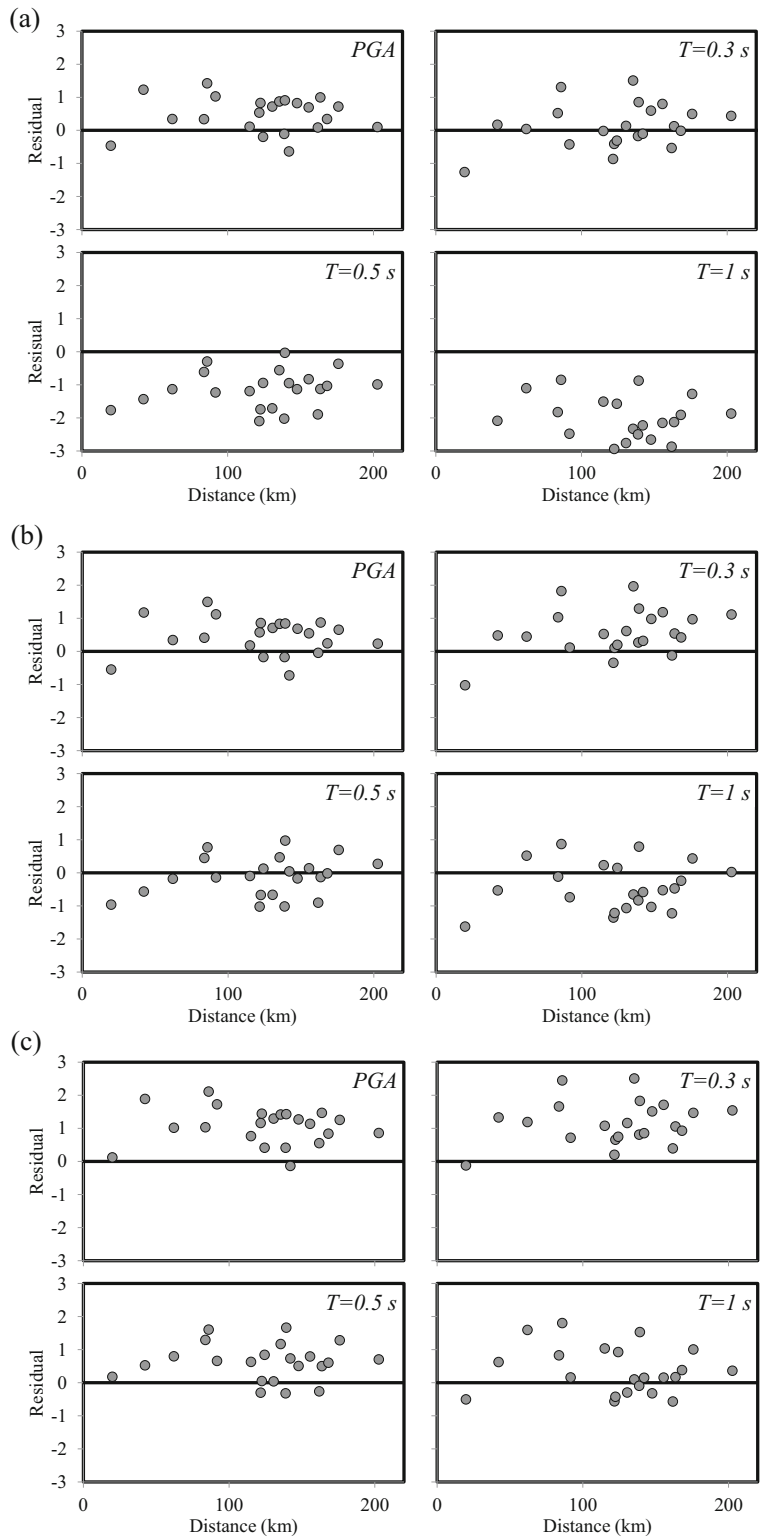
#### 4.3 Residuals for the PGA and response ordinates

Figure 6 shows the observed residuals for the PGA and response ordinates at three structural periods ( $T=0.3$ , 0.5, and 1 s) of the unusual event with that predicted by the empirical GMPEs in terms of distance from the epicenter (Ordaz et al. 1995, Fig. 6a; Youngs et al. 1997, b; Arroyo et al. 2010, c). Table 5 shows the average values of the residuals from 23 observed records for each GMPE. The residual is defined as the logarithmic difference between observations and estimations for each empirical GMPE compared herein; note that a positive or negative residual implies, respectively,

**Table 4** Percentage of points of the unusual event located above, inside, or below the limits of prediction interval of the standard deviation of predicted empirical GMPEs for earthquake with  $M_w=5.3$ 

1	Ordaz et al. (1989)			Youngs et al. (1997)			Arroyo et al. (2010)		
	2 Above	3 Inside	4 Below	5 Above	6 Inside	7 Below	8 Above	9 Inside	10 Below
PGA	9	91	0	4	96	0	70	30	0
$T=0.3$	9	87	4	17	83	0	74	26	0
$T=0.5$	0	39	61	0	100	0	30	70	0
$T=1.0$	0	13	87	0	96	4	26	74	0

**Fig. 6** Residual of PGA and response spectral ordinates at three structural periods ( $T=0.3$  s,  $T=0.5$  s,  $T=1$  s) of the moderate 13 August 2006,  $M_w$  5.3, earthquake with predicted GMPE in terms of distance. **a** Ordaz et al. (1989), **b** Youngs et al. (1997), and **c** Arroyo et al. (2010)



**Table 5** Average values of the residuals for each GMPEs for earthquake with  $M_w=5.3$ 

Reference	PGA	$T=0.3$ s	$T=0.5$ s	$T=1$ s
Ordaz et al. (1989)	0.49	0.15	-1.09	-2.02
Youngs et al. (1997)	0.44	0.58	-0.09	-0.36
Arroyo et al. (2010)	1.09	1.18	0.63	0.37

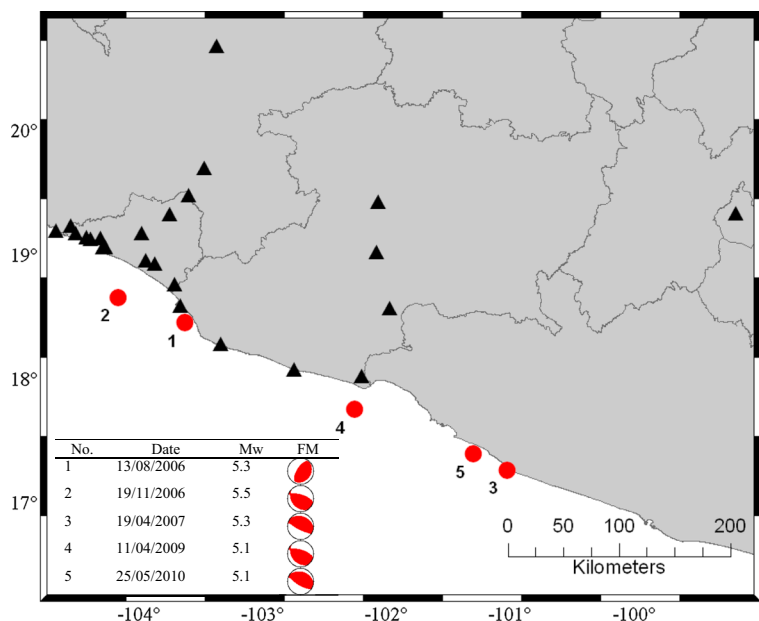
under or overestimation of the observed data set. From Fig. 6, it can be seen that the empirical GMPE of Arroyo et al. (2010) has the largest residuals or PGA and response ordinate at structural period of  $T=0.3$  s; average residuals show an underestimation of 109 and 118 %, respectively (Table 5). In addition, the empirical GMPE of Ordaz et al. (1989) has the largest residuals but for response ordinates at structural period of  $T=0.5$  and 1 s; average residuals show an overestimation of 109 and 202 %, respectively (Table 5). With the exception of GMPE of Ordaz et al. (1989) for response ordinate at structural period of  $T=0.3$  s, the average residuals are smaller for the empirical GMPE of Young et al. (1997) compared to the other GMPEs. Therefore, we consider that the empirical GMPE of Youngs et al. (1997) fit well the observed data set for this type of earthquake, and consequently, this empirical GMPE provides a reliable estimate for PGA and all spectral ordinates for the unusual event.

#### 4.4 Comparison with real data (single events)

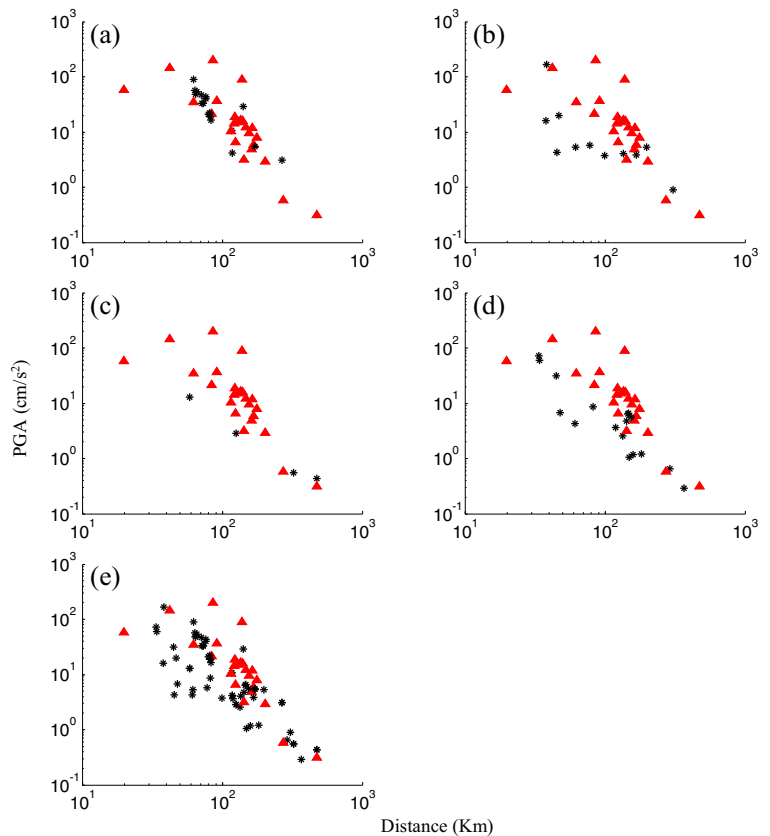
To assess the differences between the two types of earthquakes, we made a comparison of the observed PGA of the unusual event with real data. To reach this objective, we searched in the Global CMT project, IING EN, and databases of local networks for events recorded in the region whose magnitude ranged between 5.1 and 5.5, whose strike was nearly parallel to the subduction. As result, we found four events (Fig. 7) to use to compare with the unusual event, namely (a) 19 November 2006 with 7 records, (b) 19 April 2009 with 11 records, (c) 11 April 2009 with 4 records, and (d) 25 May 2010 with 19 records.

Figure 8a, b, c, d shows that in all cases of comparison, the observed ground motions of the unusual event fit or exceed those provided by the real data of the four common events. From the four cases of comparison plotted in Fig. 8a to d, the 19 November 2006 event  $M_w$  5.5 (henceforth referred to as the common event), is of particular interest for the following reasons: This event was recorded during the operation of the temporary acceleration network that we installed in the region in 2006; therefore, in addition to the seven events provided by IINGEN, we can add 11 more records that we found for this event in the database of this temporary network, totaling 18 records. Also, Fig. 7 shows that from the four events used to compare with the real data,

**Fig. 7** Location of events (real data) used to compare with the unusual event. The event analyzed in this study is represented with the *red filled circle number 1*. *Red filled circles 2, 3, 4, and 5* represent the four events with strike nearly parallel to the trench axis used in the comparisons. *Black triangles* mark the location of the acceleration stations (stations names are the same as shown in Fig. 1) that provided the strong ground motion information used in this study. See text for further details



**Fig. 8** Comparison between ground motions of the unusual event and real data. In all cases, *red triangles* show the observed PGA of the unusual event (strike perpendicular to the trench axis) analyzed in this study, and *black asterisks* represent the observed PGA of the four different events with strike nearly parallel to the trench axis used in the comparison. **a** 19 November 2006 event. **b** 19 April 2009 event. **c** 11 April 2009 event. **d** 25 May 2010 event. **e** The global comparison with the four events



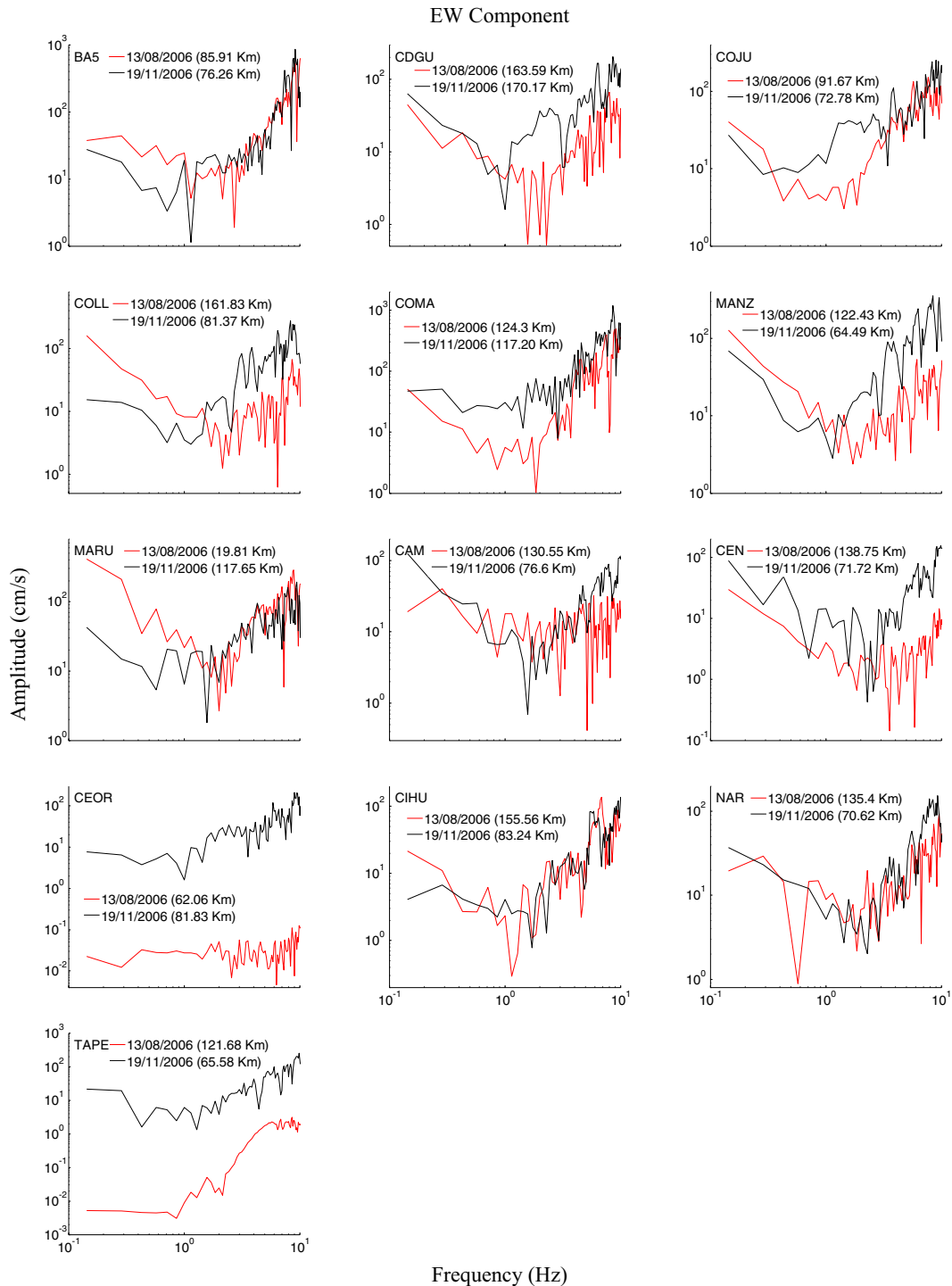
this event is the nearest to the unusual event; consequently, the tectonic environment and trajectory maintain the major resemblance with the unusual event. The comparison (Fig. 8a) shows that although the common event ( $M_w$  5.5) is of greater magnitude than the unusual event ( $M_w$  5.3), observed ground motions of the unusual event mostly locate above the center of the observed ground motions of common event. Interestingly, from the 18 stations that recorded the common event, 13 of these stations also recorded the unusual event. Figure 8e shows the global comparison of the unusual event with the four common events. We observe a similar trend, namely the points for the unusual event mostly locate above the center of the observed ground motions of the four common events. The above results resemble those observed in the comparison with the empirical GMPEs.

#### 4.5 Comparison of Fourier amplitude spectra

We found 13 stations where both the 19 November 2006 earthquake and the unusual event were recorded. Taking into account the factors mentioned above in the

sense that this common event is the closest event to the unusual event and, consequently, their tectonic environment and trajectory remain similar, we compare the acceleration. By the difference in magnitudes of both events, we expected that the spectral magnitudes of the common event ( $M_w$  5.5) would be higher than those of the unusual event ( $M_w$  5.3). We made this comparison considering the differences in distances of both events relative to each single recording station.

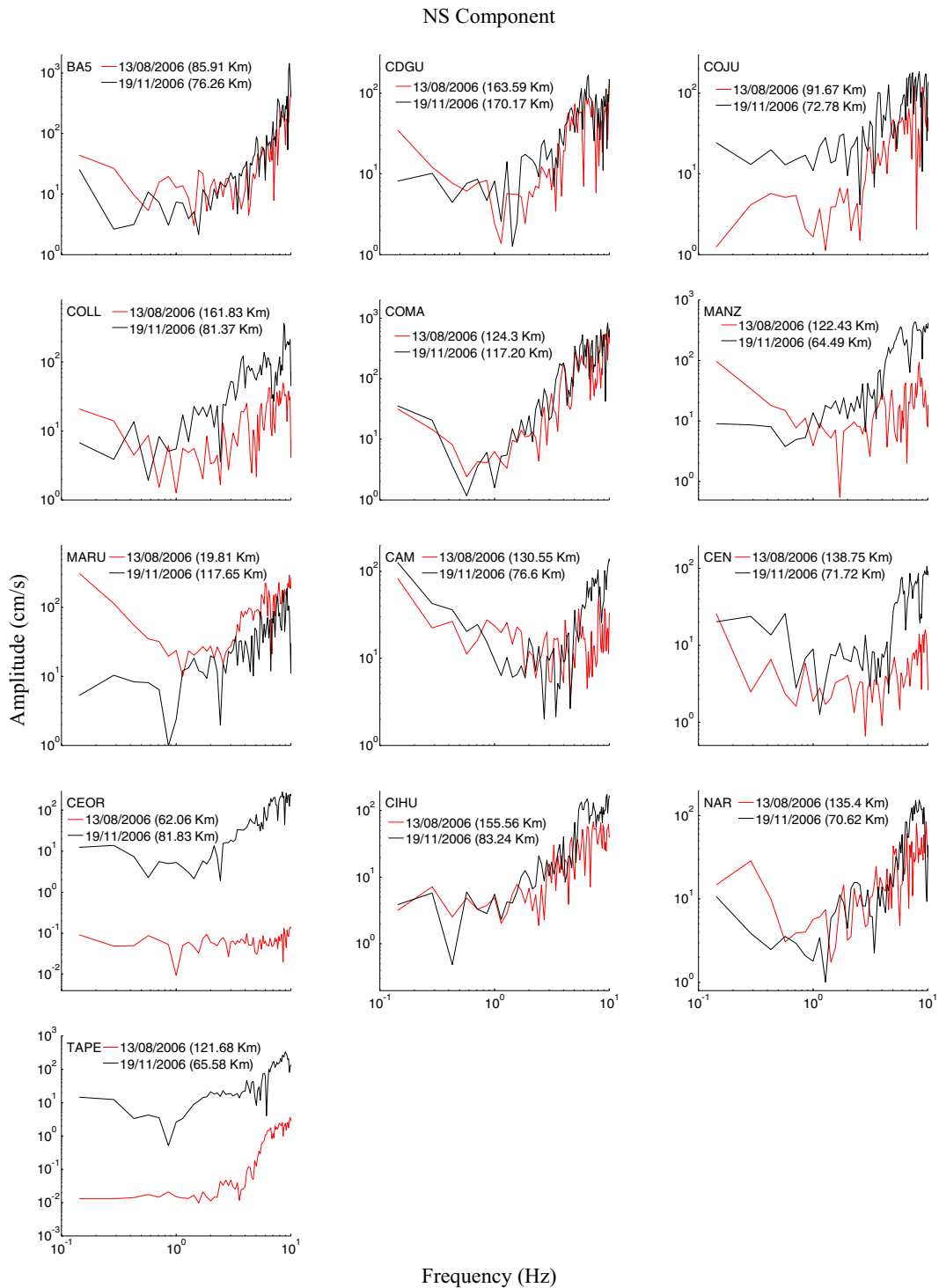
Figures 9 and 10 show the comparison in the EW and NS components, respectively. Table 6 summarizes the results of this comparison. We classified the amplitudes of the common event (in relation with the unusual event) as (H) higher, (SH) similar to higher, and (SL) similar to lower. The specific range of frequencies where this classification is presented is shown in columns 6 and 8. The comparison of source-station distances of two events (columns 2 and 3) shows that 10 stations locate close to the common event. Only three stations locate close to unusual event. Consequently, taking into account the greater proximity of the common event to the stations and, additionally, the larger magnitude of the



**Fig. 9** Comparison of acceleration Fourier spectra, east-west component, at 13 sites. 13 August 2006 unusual event (*red continuous line*) and 19 November 2006 common event (*black continuous line*)

common event ( $M_w$  5.5) relative to that of the unusual event ( $M_w$  5.3), it is expected that the Fourier spectrum of the common event should present higher spectral

amplitudes than those of the unusual event. The results show higher spectral amplitudes (H), i.e., the expected behavior, at three stations for the EW component and at



**Fig. 10** Comparison of acceleration Fourier spectra, north-south component, at 13 sites. 13 August 2006 unusual event (*red continuous line*) and 19 November 2006 common event (*black continuous line*)

**Table 6** Comparison of Fourier amplitude spectra between the common and unusual events

1 No.	2 Station	Distance source station (km)		Comparison of amplitudes in EW component		Comparison of amplitudes in NS component	
		3 Unusual event ( $M_w$ 5.3)	4 Common event ( $M_w$ 5.5)	5 Amplitude <sup>b</sup>	6 Range <sup>c</sup> (Hz)	7 Amplitude <sup>b</sup>	8 Range <sup>c</sup> (Hz)
1	MARU <sup>a</sup>	20	118	H	0.1 to 1.0	SL	0.1 to 10
2	CEOR <sup>a</sup>	62	82	H	0.1 to 10	H	0.1 to 10
3	COJU	92	73	SH	<sup>d</sup>	SH	0.1 to 10
4	COLL <sup>c</sup>	162	81	SH	<sup>d</sup>	SH	<sup>d</sup>
5	MANZ <sup>c</sup>	122	64	SH	<sup>d</sup>	SH	<sup>d</sup>
6	CEN <sup>c</sup>	139	72	SH	<sup>d</sup>	SH	0.1 to 10
7	CDGU <sup>a</sup>	164	170	SH	<sup>d</sup>	SL	0.1 to 10
8	COMA	124	117	SH	<sup>d</sup>	SL	0.1 to 10
9	BA5	86	76	SL	0.1 to 10	SL	<sup>d</sup>
10	CAM <sup>c</sup>	131	77	SL	0.1 to 10	SL	<sup>d</sup>
11	CIHU <sup>c</sup>	156	83	SL	0.1 to 10	SL	0.1 to 10
12	NAR <sup>c</sup>	135	71	SL	0.1 to 10	SL	<sup>d</sup>
13	TAPE <sup>c</sup>	122	66	H	0.1 to 10	H	0.1 to 10

<sup>a</sup> The three stations (from 13) where the common event is located at a farther distance than the unusual event. For the other 10 stations, the common event locates at closer distances than the unusual event

<sup>b</sup> Comparison of the amplitude of Fourier spectrum of the common event in relation with the unusual event: (*H*) higher, (*SH*) similar to higher, and (*SL*) similar to lower

<sup>c</sup> Indicates the frequency range in the Fourier spectrum where H, SH, or SL are present

<sup>d</sup> Indicates that the frequency range where SH or SL amplitudes are present is variable

<sup>e</sup> The seven stations where the common event is located at considerably closer distances (nearly half) than the unusual event

two stations for the NS component. At these stations, the common event shows markedly higher spectral amplitudes (in all the frequency range) than does the unusual event. The common event shows spectral amplitudes in comparison with unusual event that go from similar to higher (SH) in six stations for the EW component and in four stations for the NS component. Lastly, the common event shows spectral amplitudes in comparison with the unusual event that go from similar to lower (SL) in four stations for the EW component and in seven stations for the NS component. To judge cases SH and SL, it is necessary to take into account that the frequency range where SH and SL are observed, is variable, and in several specific ranges, the common event shows clearly lower amplitudes than the unusual event. Also, observe that these stations locate nearer to the common event (about half that for the unusual event). The above results maintain their resemblance with those observed in the comparison with empirical GMPEs and with those observed in the comparison with real data (PGA).

## 5 Conclusions

We present a study of a moderate, unusual earthquake (13 August 2006, 5.3  $M_w$ ) that has a focal mechanism with nodal planes oriented practically perpendicular to those of the great majority of the earthquakes occurring along the subduction zone of the Mexican Pacific Coast.

To evaluate the unusual event, we conduct three different comparisons. The first is to compare the observed ground motions with three GMPEs adequate for the region. The second is to compare observed ground motions of the unusual event with real data of single events with strike nearly parallel to subduction. The third is to compare the Fourier spectrum of the unusual event with that of a single selected event with strike parallel to the trench.

To conduct an adequate assessment between ground motions of the unusual event and GMPEs, we conduct a study to verify that the stations involved in this study are



free of site effects. Acceleration time series of the unusual event were used to plot H/V ratios for the 24 sites that recorded the unusual event. As a result, we observe that 23 of the 24 sites correspond to a rock site and only 1 site corresponds to soft soil; consequently, we remove this station from the analysis.

Summarizing the results of the three different comparisons conducted herein to evaluate ground motions of the unusual event, (i) the comparisons with three empirical GMPEs show that in 2 of the 12 comparisons (PGA and three different spectral ordinates), the observed points locate below the empirical GMPE of Ordaz et al. (1989), for the rest of the 10 comparisons the points lie within or exceed the 90 % confidence intervals of the empirical GMPEs; (ii) the comparison with real data (single events which strike nearly parallel to the trench) shows that the points for the unusual event locate in a range above the center of the observed ground motions of the four common events; and (iii) the comparison of the Fourier spectrum of the unusual event with a selected event with strike parallel to the subduction zone shows that the common event presents similar to lower amplitudes in relation with the unusual event.

## 6 Data and resources

The Global Centroid Moment Tensor (CMT) project database was searched using the [www.globalcmt.org/CMTsearch.html](http://www.globalcmt.org/CMTsearch.html) (last accessed 10 January 2015). The US Geological Survey's National Earthquake Information Center (NEIC) was searched using the <http://earthquake.usgs.gov/earthquakes/search/>. Maps were created by using Arc GIS version 9.3. Graphics and plots were created using Matlab version 7.0.

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